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(54) METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR TESTING NETWORK ELEMENTS OF AN IN-BAND NETWORK TELEMETRY CAPABLE NETWORK

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H04L 12/26 (2006.01)
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CPC ***H04L 41/145*** (2013.01); ***H04L 41/12*** (2013.01)

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CPC H04L 41/145; H04L 41/12; H04L 41/24; H04L 41/0803
See application file for complete search history.

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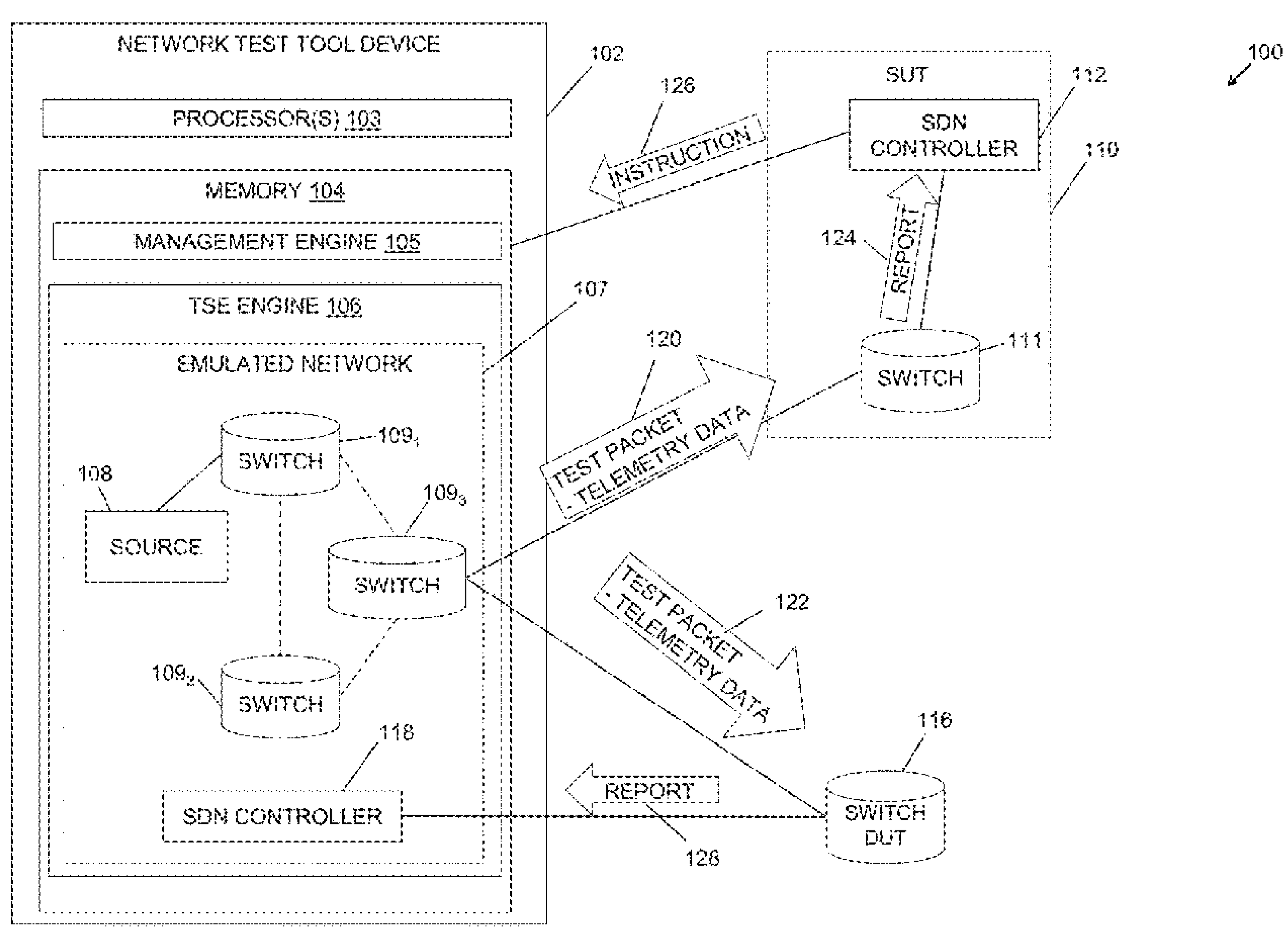
Primary Examiner — Siren Wei

(57) **ABSTRACT**

Methods, systems, and computer readable media for testing network elements of an in-band telemetry (INT)-capable network are disclosed. One exemplary method includes generating, by a network test tool device, at least one INT test system data packet that includes emulated INT metadata that represents telemetry parameters corresponding to a plurality of emulated network devices. The method also includes sending the at least one INT test system data packet to an INT sink device and generating, by the INT sink device, an INT telemetry report derived from the INT metadata extracted from the at least one INT test system data packet. The method also includes forwarding the generated INT telemetry report to a software defined network (SDN) controller entity.

15 Claims, 5 Drawing Sheets



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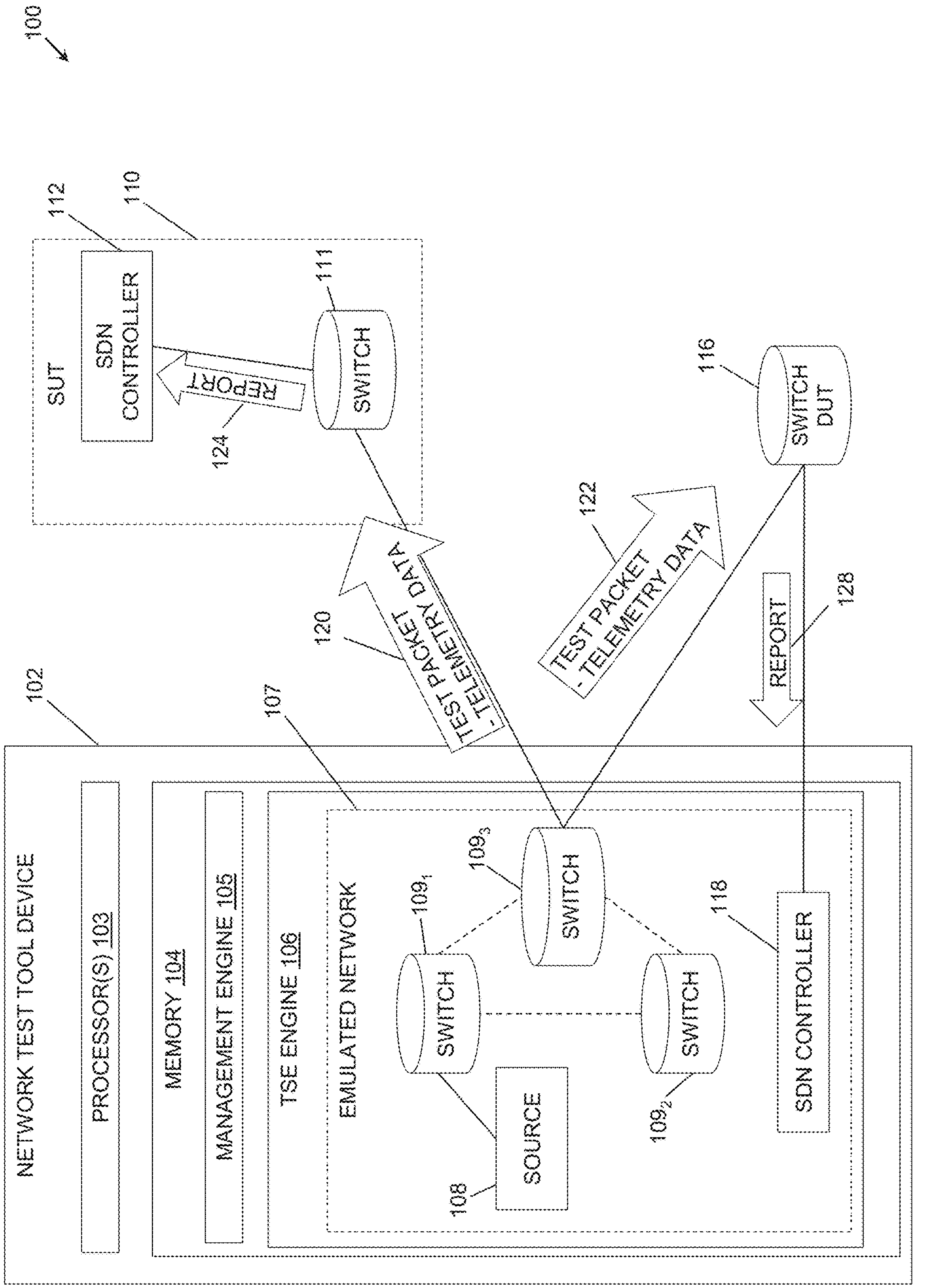

100
NETWORK TEST TOOL DEVICE
PROCESSOR(S) 103
MEMORY 104
MANAGEMENT ENGINE 105
TSE ENGINE 106
EMULATED NETWORK
SWITCH
SWITCH
SWITCH
SOURCE
SDN CONTROLLER
102
107
109_1
109_2
109_3
108
118
SUT
SDN CONTROLLER
SWITCH
REPORT
110
111
112
124
TEST PACKET - TELEMETRY DATA
120
TEST PACKET - TELEMETRY DATA
122
SWITCH DUT
116
REPORT
128

FIG. 1

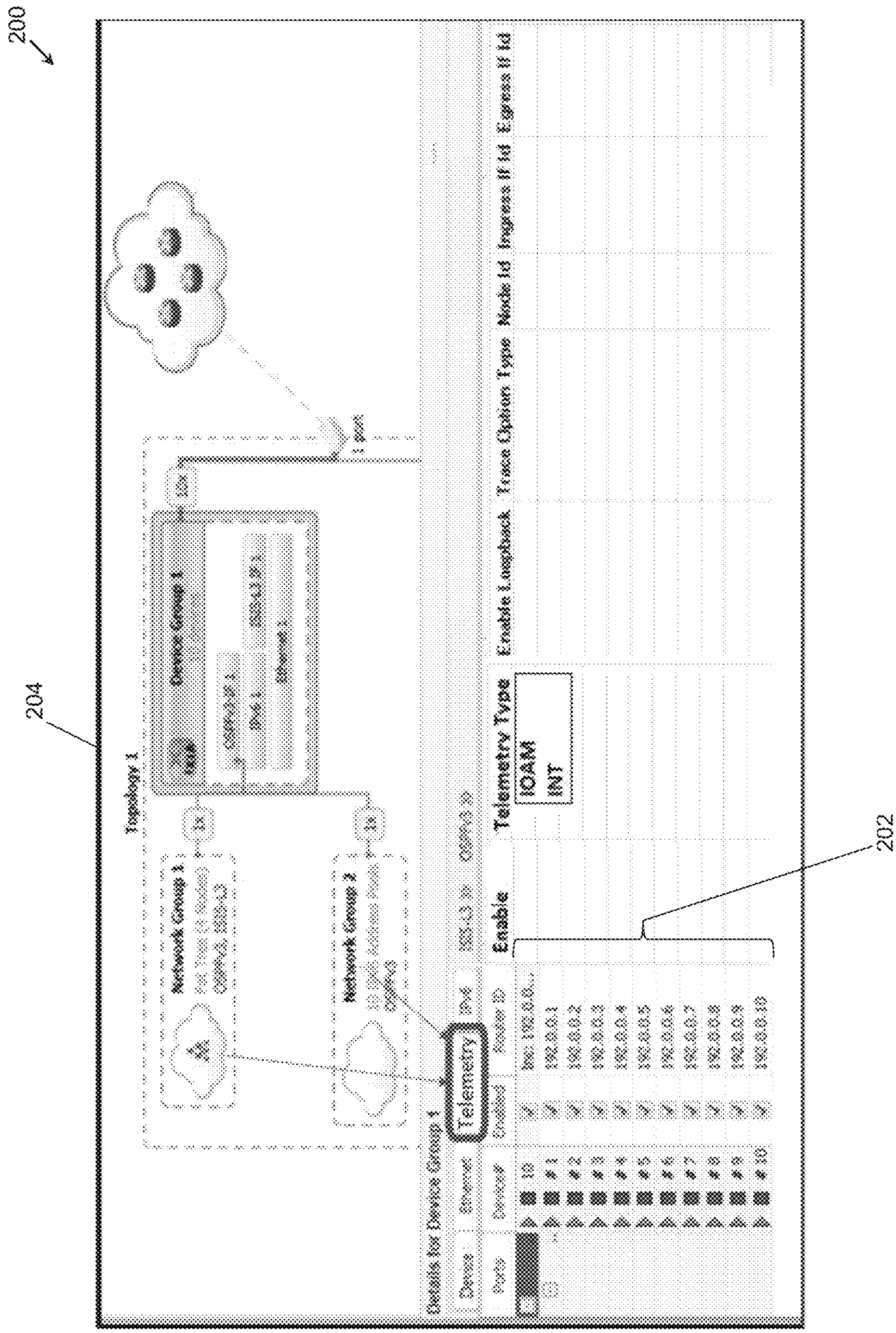
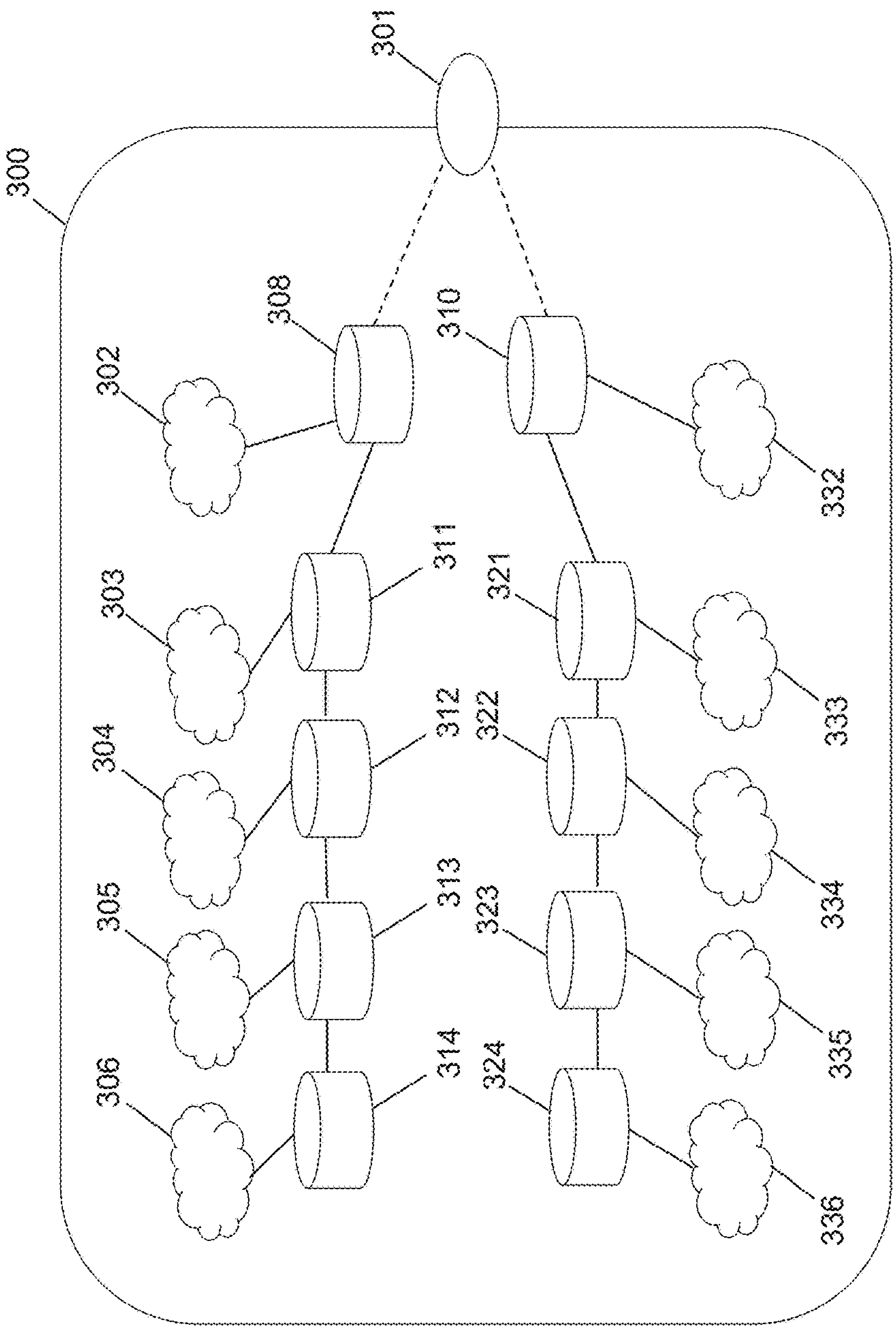

200
204
202
Topology 1
Network Group 1
Network Group 2
Device Group 1
Details for Device Group 1
Telemetry
Enable
Telemetry Type
IOAM
INT
Enable Loopback
Trace Option Type
Node Id
Ingress If Id
Egress If Id

FIG. 2


300
301
302
303
304
305
306
308
310
311
312
313
314
321
322
323
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332
333
334
335
336

FIG. 3

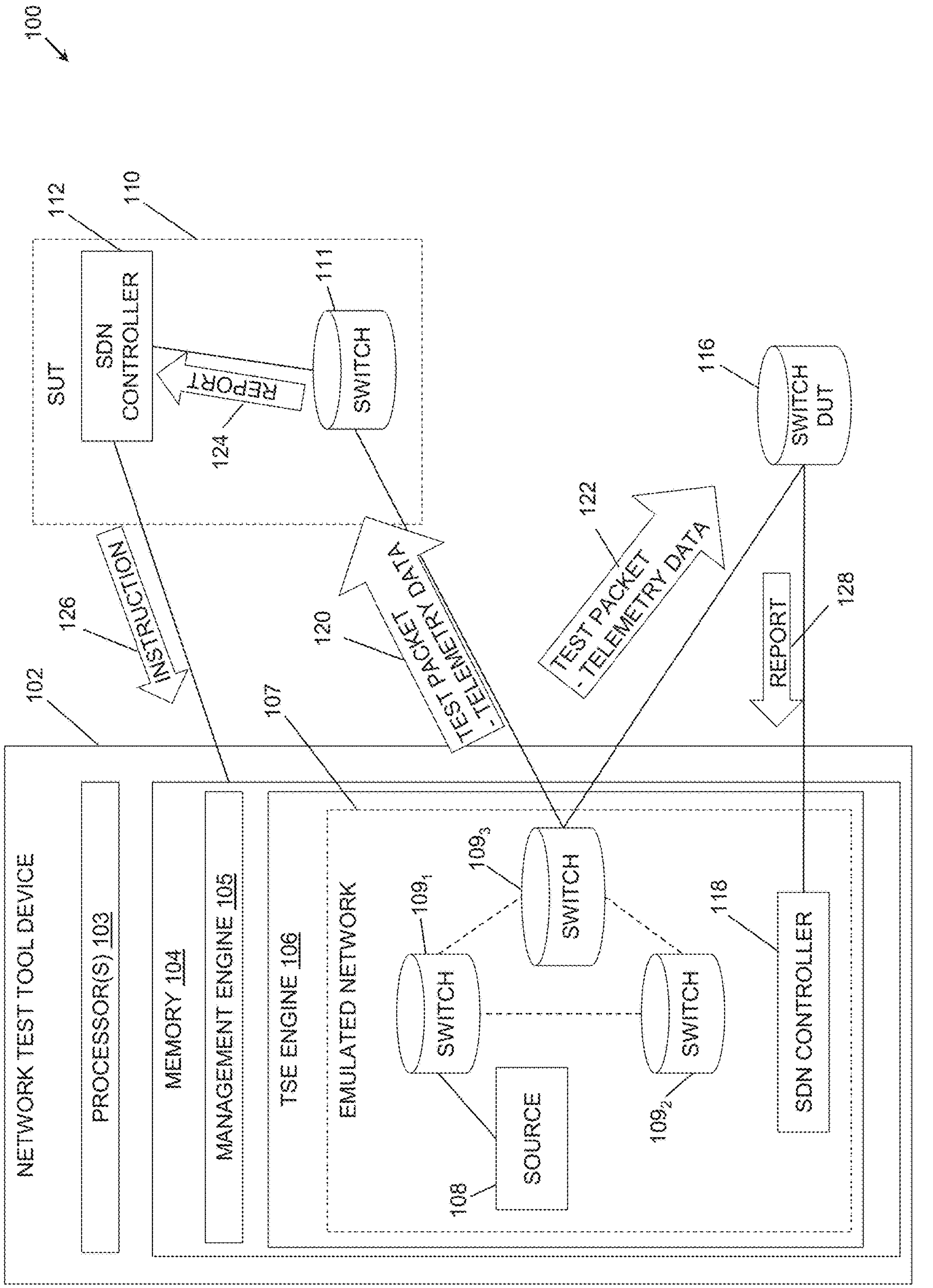
100
NETWORK TEST TOOL DEVICE
102
PROCESSOR(S) 103
MEMORY 104
MANAGEMENT ENGINE 105
TSE ENGINE 106
107
EMULATED NETWORK
SWITCH
109_1
SWITCH
109_3
SWITCH
109_2
SOURCE
108
SDN CONTROLLER
118
SUT
110
SDN CONTROLLER
112
SWITCH
111
REPORT
124
INSTRUCTION
126
TEST PACKET - TELEMETRY DATA
120
TEST PACKET - TELEMETRY DATA
122
SWITCH DUT
116
REPORT
128

FIG. 4

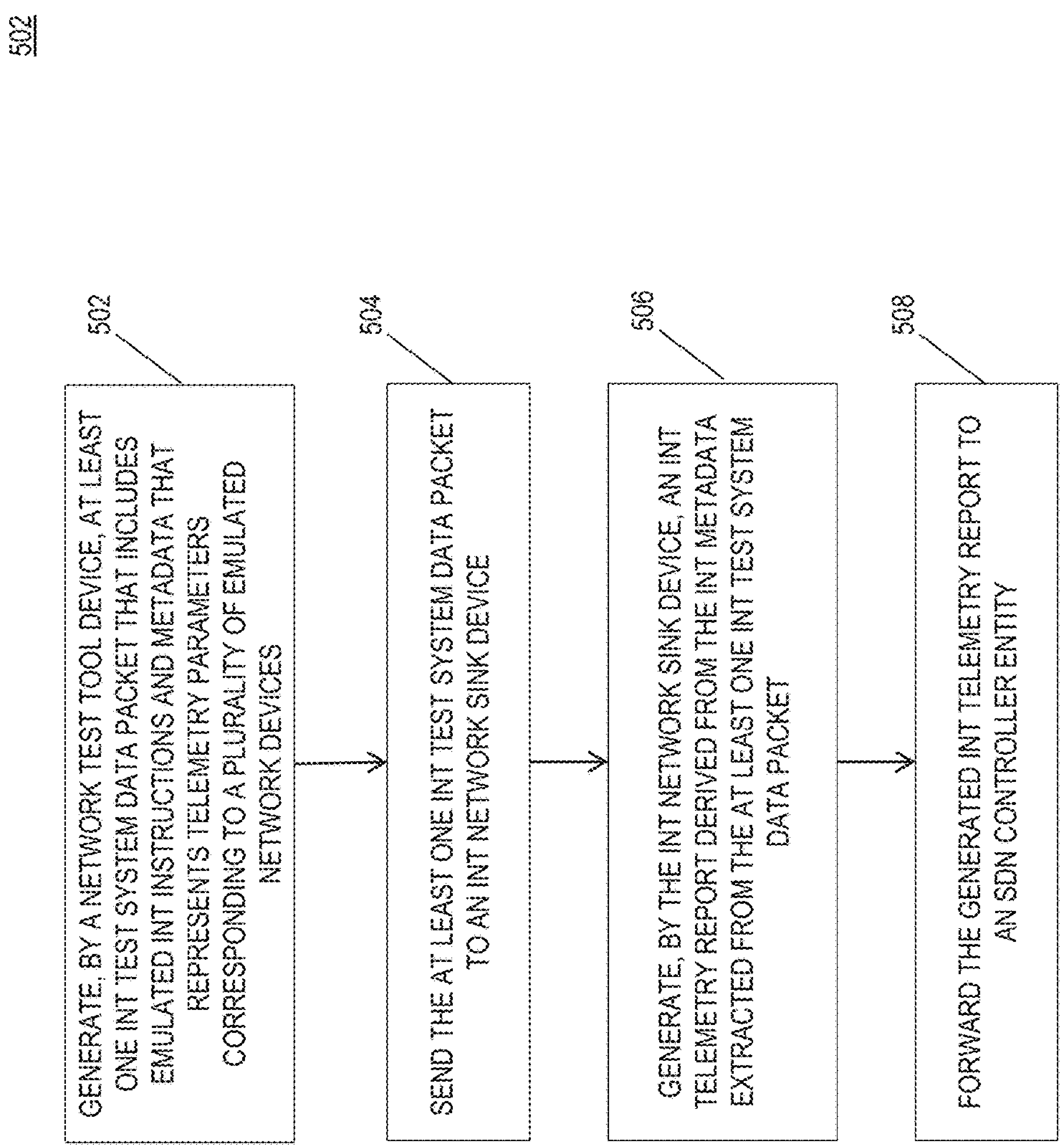
502
GENERATE, BY A NETWORK TEST TOOL DEVICE, AT LEAST ONE INT TEST SYSTEM DATA PACKET THAT INCLUDES EMULATED INT INSTRUCTIONS AND METADATA THAT REPRESENTS TELEMETRY PARAMETERS CORRESPONDING TO A PLURALITY OF EMULATED NETWORK DEVICES
502
SEND THE AT LEAST ONE INT TEST SYSTEM DATA PACKET TO AN INT NETWORK SINK DEVICE
504
GENERATE, BY THE INT NETWORK SINK DEVICE, AN INT TELEMETRY REPORT DERIVED FROM THE INT METADATA EXTRACTED FROM THE AT LEAST ONE INT TEST SYSTEM DATA PACKET
506
FORWARD THE GENERATED INT TELEMETRY REPORT TO AN SDN CONTROLLER ENTITY
508

FIG. 5

METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR TESTING NETWORK ELEMENTS OF AN IN-BAND NETWORK TELEMETRY CAPABLE NETWORK

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/181,309, filed Nov. 5, 2018, the disclosure of which is herein incorporated by reference in their entirety.

TECHNICAL FIELD

The subject matter described herein relates to network equipment testing. More particularly, the subject matter described herein relates to methods, systems, and computer readable media for testing network elements of an in-band network telemetry (INT)-capable network.

BACKGROUND

In-band network telemetry (INT) is a framework configured to permit the collection and reporting of a network state, by the data plane, without requiring any intervention on the part of the control plane. In the INT architectural model, data packets contain INT header fields, a part of which is interpreted as telemetry instructions by network devices. The instructions contained in the header fields instruct INT-capable devices what INT metadata needs to be collected and written into the INT packet as the packet traverses the network. The INT system architecture includes both INT traffic sources and INT traffic sinks. A traffic source is a network element that is configured to embed the instructions in normal data packets. Likewise, traffic sinks are network elements that are configured to retrieve the collected results of these instructions in the form of device-specific information, thereby allowing the traffic sinks or a central controller to monitor the exact data plane state that the data packets observed while being forwarded within the network. At present, conducting INT-based testing of traffic sinks and associated network controllers is difficult due to the numerous network elements that are needed to produce realistic and accurate results.

Accordingly, there exists a need for methods, systems, and computer readable media for testing network elements of an INT-capable network.

SUMMARY

According to one aspect, the subject matter described herein includes a method for testing network elements of an INT-capable network. The method includes generating, by a network test tool device, at least one test system data packet that includes emulated INT instructions and metadata that represents telemetry parameters corresponding to a plurality of emulated network devices. The method also includes sending the at least one test system data packet to an INT sink device and generating, by the INT sink device, an INT telemetry report derived from the INT metadata extracted from the at least one INT test system data packet. The method also includes forwarding the generated INT telemetry report to a software defined network (SDN) controller entity.

In one example of the method, the SDN controller entity utilizes the INT telemetry report to assess the performance of an emulated network composed by the plurality of emulated network devices.

In one example of the method, the INT sink device is either a device under test or a switch device in a system under test.

In one example of the method, the SDN controller entity generates an instruction packet containing one or more instructions that direct the network test tool device to modify a network topology of the emulated network.

In one example of the method, the network test tool device modifies the emulated INT metadata included in the at least one INT test system data packet to record a change in the modified network topology.

In one example of the method, the telemetry parameters represent a user-defined test case specifying at least one predefined network event or at least one predefined network condition.

In one example of the method, the SDN controller entity provides, to a management engine in the network test tool device, a status description indicative of real-time control functionality in response to the receiving the INT telemetry report.

According to another aspect, the subject matter described herein includes a system for testing network elements of an INT-capable network. The system includes at least one processor and a memory. The system also includes a network test tool device comprising at least one processor, a memory, an INT traffic source emulation engine that when stored in memory and executed by the at least one processor is configured for generating at least one INT test system data packet that includes emulated INT instructions and metadata that represents telemetry parameters corresponding to a plurality of emulated network devices, and a management engine that when stored in memory and executed by the at least one processor is configured for sending the at least one INT test system data packet. The system further includes an INT network sink device configured for receiving the at least one INT test system data packet, for generating an INT telemetry report derived from the INT metadata extracted from the at least one INT test system data packet, and for forwarding the generated INT telemetry report to a software defined network (SDN) controller entity.

In one example of the system, the SDN controller entity utilizes the INT telemetry report to assess a performance of an emulated network composed by the plurality of emulated network devices.

In one example of the system, the INT sink device is either a device under test or a switch device in a system under test.

In one example of the system, the SDN controller entity generates an instruction packet (e.g., at least one non-INT packet) containing one or more instructions that direct the network test tool device to modify a network topology of the emulated network or the INT instruction, thereby modifying the type of INT metadata to be recorded by the INT transit devices.

In one example of the system, the network test tool device modifies the emulated INT metadata included in the at least one test system data packet to monitor the change in network topology.

In one example of the system, the telemetry parameters represent a user-defined test case specifying at least one predefined network event or at least one predefined network condition.

In one example of the system, the SDN controller entity provides to the network test tool device a status description indicative of real-time control functionality in response to the receiving the INT telemetry report.

As used herein, an INT header refers to a packet header that carries INT information. Examples of INT headers include a hop-by-hop header and a destination header.

As used herein, an INT packet refers to any packet containing an INT header.

As used herein, an INT instruction includes embedded packet instructions that indicate which INT metadata to collect. The collected data is written into an INT header.

As used herein, an INT source entity refers to a trusted entity that creates and inserts INT headers into the INT packets. The INT headers contain, at a minimum, INT instructions that indicate what data is to be collected. Examples of INT source entities include applications, end-host networking stacks, hypervisors, network interface controllers, and the like.

As used herein, an INT sink refers to a trusted entity that extracts the INT headers from INT packets and collects the path state information contained in the INT headers. The INT sink device is responsible for removing INT headers so as to make INT transparent to upper layers.

As used herein, and INT transit hop refers to a networking device that adds its own INT metadata to an INT packet by following the INT instructions in the INT header.

As used herein, INT metadata refers to telemetry information that is included in the INT header.

As used herein, an SDN controller entity can refer to either an SDN controller device or an SDN controller emulation.

The subject matter described herein can be implemented in software in combination with hardware and/or firmware. For example, the subject matter described herein can be implemented in software executed by a processor. In one exemplary implementation, the subject matter described herein can be implemented using a non-transitory computer readable medium having stored thereon computer executable instructions that when executed by a processor of a computer control the computer to perform steps. Exemplary computer readable media suitable for implementing the subject matter described herein include non-transitory computer-readable media, such as disk memory devices, chip memory devices, programmable logic devices, and application specific integrated circuits. In addition, a computer readable medium that implements the subject matter described herein may be located on a single device or computing platform or may be distributed across multiple devices or computing platforms.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the subject matter described herein will now be explained with reference to the accompanying drawings, wherein like reference numerals represent like parts, of which:

FIG. **1** is a block diagram illustrating an exemplary system for testing network elements of an INT-capable network according to an embodiment of the subject matter described herein;

FIG. **2** is a block diagram illustrating an exemplary user interface for testing network elements of an INT-capable network according to an embodiment of the subject matter described herein;

FIG. **3** is a block diagram illustrating an exemplary logical representation of a simulation topology of an INT-capable network emulated by the proposed network test tool device according to an embodiment of the subject matter described herein;

FIG. **4** is a block diagram illustrating an exemplary system for providing instructions for modifying the telemetry information to be recorded by the INT-capable network devices emulated by the proposed network test tool device according to an embodiment of the subject matter described herein; and

FIG. **5** is a flow chart illustrating an exemplary process for testing network elements of an INT-capable network according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION

In accordance with the subject matter disclosed herein, systems, methods, and computer readable media for testing network elements of an INT-capable network are provided. In some embodiments, the disclosed subject matter includes a network test tool device configured for testing a P4-enabled INT sink device or a network element that utilizes the INT data, such as a SDN controller. Notably, the network test tool device can be configured to intelligently insert in-band telemetry metadata within INT test system data packets generated by the test tool device. In some embodiments, the telemetry metadata comprises telemetry data parameters and associated values that are initially defined by a user (e.g., via a control panel). In particular, the network test tool device can establish the telemetry parameters in such a manner that a specific network event or test condition can be emulated by the network test tool. The network test tool device subsequently sends the generated INT test system data packets to a DUT and/or SUT to test performance monitoring. Depending on the presence of INT header inside the test system data packets, the generation of a telemetry report message by an INT sink device can be triggered. The generated telemetry report message may then be forwarded to a network monitoring element, such as an SDN controller entity.

Reference will now be made in detail to exemplary embodiments of the present invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

FIG. **1** illustrates of a block diagram of a test environment network **100**. A logical architecture of test environment network **100** is depicted in FIG. **1** as comprising a network test tool device **102**, an INT capable system under test (SUT) **110**, and an INT capable switch device under test (DUT) **116**. In some embodiments, network test tool device **102** may include one or more processors **103** and a memory **104** that are collectively utilized to support an INT test management engine **105** and an INT traffic source emulation (TSE) engine **106**. In some embodiments, processor(s) **103** may include a central processing unit (e.g., a single core or multiple processing cores), a microprocessor, a microcontroller, a network processor, an application-specific integrated circuit (ASIC), or the like. Likewise, memory **104** may comprise random access memory (RAM), flash memory, a magnetic disk storage drive, and the like. In some embodiments, memory **104** may be configured to store management engine **105** and TSE engine **106**.

In some embodiments, network test tool device **102** and/or management engine **105** is configured to receive messages and instructions from a client application or a test console utilized by a system administrator. In some embodiments, the test console (not shown in FIG. **1**) is an integral part of the network test tool device **102** includes a test console element that can be presented to a user or system administrator in the form of a graphical user interface (GUI). In alternate embodiments, the test console may be communicatively connected to network test tool device **102** via a wired or wireless connection. Using the test console, the system administrator can issue instructions that define a test case for testing either a DUT or SUT in test environment network **100**. For example, the instructions provided by the system administrator can include parameters for establishing an emulated network that comprises a plurality of emulated network devices (e.g., emulated switches, routers, and hosts) that is subjected to and/or made to experience a specific network event or network condition. In particular, the system administrator can design or configure an emulated network (e.g., emulated network **107**) for a test environment to include any number of emulated network devices that serve as either an INT source element and/or an INT transit element for an INT sink device that is to be subjected to INT network testing via the data plane. For example, FIG. **2** illustrates an exemplary screen display **200** that presents a user interface that can be utilized by a system administrator to design or select one or more individual emulated network components **202** for an emulated device group **204**. For example, a system administrator can utilize screen display **200** to select a plurality of emulated components **202** that make up the emulated network generated by TSE engine **106**. In some embodiments, the generation and presentation of screen display **200** is supported by management engine **105** and/or TSE engine **106**.

Referring back to FIG. **1**, the system administrator can issue test system data packet configuration instructions that configure the network testing tool device **102** and/or the TSE engine **106** to generate INT test system data packets that contain emulated INT metadata that makes the representation that the packet traversed and was subsequently modified by emulated network devices of an emulated network (i.e., an indication that represents as if these network devices were actually traversed by the INT data packets). The test system data packets also included emulated INT instructions that indicate the type of INT metadata that is to be recorded (e.g., at each of the transit points/elements). Notably, network test tool device **102** and/or TSE engine **106** can be instructed to generate representative INT test system data packets that are used to test a DUT or a SUT, or any network element that utilizes the in-band telemetry data. Examples of the DUT include an INT sink device, a INT enabled network switch or router, an SDN controller entity, or a segment routing path computation element.

In some embodiments, the test system data packet configuration instructions sent by the system administrator are directed to management engine **105** in network test tool device **102**. Management engine **105** is configured to utilize the instructions and parameters received from the administrator's test console to formulate the logical architecture and layout of an emulated network that is represented at least in part in the emulated INT metadata to be included in the test system INT data packets (e.g., emulated network **107** generated by TSE engine **106**). Management engine **105** further defines the network telemetry parameters specified in the INT test system data packets to be generated by TSE engine **106**. To illustrate, emulated network **107** may be defined as having an emulated source entity **108** and emulated switches $\mathbf{109}_{1\ldots3}$. Although only three emulated switches $\mathbf{109}_{1\ldots3}$ are depicted in emulated network **107** in FIG. **1**, additional switches can be utilized without departing from the scope of the disclosed subject matter. In some alternate embodiments where only a DUT is tested (as opposed to an entire SUT), emulated network **107** may also include an SDN controller emulation **118**. After constructing emulated network **107**, TSE engine **106** is configured to generate INT test system data packets based on the emulated network represented in the test system data packet generation instructions. In some embodiments, management engine **105** forwards the test instructions and the INT test system packet parameters to TSE engine **106** for test system data packet generation processing.

More specifically, after receiving the test system data packet generation instructions and packet parameters from management engine **105**, TSE engine **106** is configured to generate INT test system data packets associated with an emulated network **107** that is defined by the parameters provided by management engine **105**. Notably, the INT test system data packet includes telemetry data that represents an INT source and one or more INT transit network devices embedded telemetry metadata in INT test system data packets according to specifications, such as P4 in-band telemetry. More specifically, the telemetry metadata is embedded in between other protocol headers (such as IPv6, TCP/UDP, Geneve, etc.) of the test system data packet as defined in the INT specification.

To illustrate, TSE engine **106** may be configured to generate an INT test system data packet that includes emulated INT metadata indicative of traversing the source entity **108**, switch $\mathbf{109}_1$, and switch $\mathbf{109}_3$. Alternatively, TSE engine **106** can generate an INT test system data packet containing emulated INT metadata that indicates that the packet traversed the source entity **108**, switch $\mathbf{109}_1$, switch $\mathbf{109}_2$, and switch $\mathbf{109}_3$. Although the telemetry metadata included in the INT test system data packets (e.g., INT records of each transit device) indicates that the packet traversed a plurality of network elements in the emulated network, the INT test system data packets are generated by TSE engine **106** to include all of the representative telemetry metadata at the time of creation (i.e., the INT test system data packets do not actually traverse the network elements of emulated network **107** and collect INT data, but rather feigns and/or fabricates this data as a pretense).

After generating the test system data packets, TSE engine **106** is responsible for sending the test system data packets to an INT sink device under test (e.g., switch DUT **116**) and/or a system under test (e.g., SUT **110**). For example, FIG. **1** depicts network test tool device **102** and/or TSE engine **106** as generating and issuing an INT test system data packet **120** that includes telemetry data. In this scenario, the telemetry data may include INT data that indicates that the packet originated at source entity **108** and traversed switch $\mathbf{109}_1$ and switch $\mathbf{109}_3$ (e.g., a "2-record" INT packet). In some embodiments, TSE engine **106** directs INT test system data packet **120** via a transmit port of network test tool device **102** to a system under test (e.g., SUT **110**). Notably, INT test system data packet **120** is received by a INT capable switch device **111**, which can be operating as an INT sink device in SUT **110**. Likewise, TSE engine **106** can be configured to send a test system data packet via a transmit port of network test tool device **102** to a specific DUT. For example, FIG. **1** illustrates that network test tool device **102** sends a test system data packet **122** to switch DUT **116**, which is functioning as an INT sink device.

After receiving INT test system data packet **122**, switch DUT **116** is configured to extract the INT telemetry data contained in the test system data packet. In some embodiments, switch DUT **116** is configured to remove the INT headers included in the INT test system data packet received from network test tool device **102**. Notably, the INT headers contain the telemetry metadata inserted by network test tool device **102**.

After extracting the telemetry metadata from the test system data packet **120**, INT capable switch device **111** can analyze the extracted data to determine whether a telemetry report needs to be generated and sent to an SDN controller device **112** in SUT **110**.

Similarly, after receiving the INT test system data packet **122**, switch DUT **116** can extract the telemetry data and determine whether a telemetry report needs to be generated and sent to an SDN controller emulation **118** in network test tool device **102**. Specifically, SDN controller emulation **118** is an emulated SDN controller entity that logically exists in emulated network **107**.

After extracting the telemetry metadata from the test system data packet, switch DUT **116** is configured to analyze the telemetry metadata and determine whether a telemetry report message is to be generated. As used herein, a telemetry report message can be defined as a message sent by an INT sink device to a monitoring system element (e.g., an SDN controller). A telemetry report message includes a 'snapshot' of the original test system data packet (e.g., the inner and outer packet headers). Based on the contents of the original test system data packet, the generation of a telemetry report message can be triggered. In some embodiments, the telemetry report message can be encapsulated by IP and UDP. Notably, such encapsulation facilitates the forwarding of the telemetry report message from the reporting DUT through the data network and to the destination monitoring SDN controller.

For example, the generation of telemetry reports can be triggered when one or more flow parameters of the test system data packets match predefined flow definitions. In some embodiments, the INT sink device can utilize a telemetry access control list, or flow watch list, that determines which test system data packets to monitor by detecting matching parameters in packet header fields. Telemetry report messages are generated for the test system INT data packets that include parameters that match predefined definitions (e.g., tuple data) specified in the access control list or flow watch list. Notably, telemetry report messages include information regarding the path (e.g., source/origin information and transit element information) that INT packets traverse in a network in addition to other telemetry metadata, such as hop latency and queue occupancy at each of the network elements.

In some embodiments, an INT sink device may initiate the generation of a telemetry report message whenever a packet matching a tracked application flow is received or transmitted on a different path than previously received packets. Further, the generation of a telemetry report message can be triggered if the telemetry data indicates a significant change in latency is experienced at a particular hop. The generation of telemetry report messages can be triggered by various events, such as flow monitoring, queue congestion, and packet drops.

In some embodiments, network test tool device **102** includes an SDN controller emulation **118**. Notably, SDN controller emulation **118** comprises an emulation element residing in emulated network **107** and is configured to receive and process the telemetry metadata report information contained in the telemetry report message **128** received from a switch DUT **116** via a receive port on the network test tool device **102**. For example, SDN controller emulation **118** can extract telemetry data from the telemetry report message **128** and determine whether changes or modifications to emulated network **107** is necessary for continued testing of the INT sink device, i.e., switch DUT **116**. Specifically, SDN controller emulation **118** can decide to change emulated network **107**. In some embodiments, the SDN controller utilizes the INT telemetry report to assess the performance of the emulated network composed by the plurality of emulated network devices. This assessment based on the telemetry report message can be used to validate the network assessment capability of the SDN controller device using the INT information. After arriving at this decision, SDN controller emulation **118** can issue an instruction message (e.g., at least one non-INT packet) that is communicated via a different protocol (e.g., not P4-INT protocol) to management engine **105**. This is described below in additional detail in the description of FIG. **4**. In some embodiments, the SDN controller emulation **118** generates a non-INT instruction message containing one or more instructions that direct the network test tool device to modify a network topology of the emulated network and/or modify the INT instructions to record a different set of INT metadata within the at least one INT test system data packet than previous INT test system data packets.

In some embodiments, network test tool device **102** is communicatively connected (via a wireless or wired connection) to SDN controller device **112** in SUT **110**. SDN controller device **112** is configured to receive and process the telemetry metadata report information contained in the telemetry report message **124** received from a switch device **111** in SUT **110**. For example, SDN controller device **112** can extract telemetry data from the telemetry report message **124** and determine whether changes or modifications to emulated network **107** is necessary for continued testing of SUT **110**. Specifically, SDN controller device **112** can decide to change emulated network **107**. In some embodiments, the SDN controller device utilizes the INT telemetry report to assess the performance of the emulated network composed by the plurality of emulated network devices. This assessment based on the telemetry report message can be used to validate the network assessment capability of the SDN controller device using the INT information. After arriving at this decision, SDN controller device **112** can issue an instruction message (e.g., at least one non-INT packet) that is communicated via a different protocol (e.g., not P4-INT protocol) to management engine **105** in network test tool device **102**. This is described below in additional detail in the description of FIG. **4**. In some embodiments, the SDN controller device generates a non-INT instruction message containing one or more instructions that direct the network test tool device to modify a network topology of the emulated network and/or modify the INT instructions to record a different set of INT metadata within the at least one INT test system data packet than previous INT test system data packets.

Upon receiving the instruction message **126** from SDN controller device **112**, management engine **105** can logically modify emulated network **107** and/or change the type of metadata that the subsequent INT test system data packets should carry (e.g., instruction message **126** may request to include "queue occupancy" along with "hop latency"). More specifically, INT instructions can be modified by management engine **105** to record a different set of INT metadata within the INT test system data packet as compared to previously processed INT test system data packets. Furthermore, management engine **105** may generate data packet instructions for directing TSE engine **106** to generate test system data packets containing telemetry metadata that indicates that traversal of the packet through the modified emulated network **107**. As indicated above, the telemetry metadata included in the test system data packets represents or specifies a packet traversal that did not actually occur (e.g., in a physical network).

FIG. **3** illustrates a logical representation of a simulated topology **300** corresponding to an emulated network that is generated by a network test tool device and is used to generate INT test system data packets (by the TSE) upon receiving telemetry instructions from a system administrator. In particular, simulated topology **300** represents the emulated network that is designed and managed by a user interface presented on screen display **200** shown in FIG. **2**. Simulated topology **300** includes a plurality of simulated and/or emulated network elements **308-324** that can be used to conduct INT testing on an INT-capable SUT and/or INT sink DUT. Specifically, simulated topology **300** includes a first emulation entity, e.g., a router emulation **308** and a second emulation entity, e.g., router emulation **310**, each of which represents an emulated INT enabled router or switch that has a direct communication connection to physical test port **301** (e.g., a part of network test tool device **102** in FIG. **1**). Further, router emulation **308** is logically coupled to simulated elements **311-314** in series. As used herein, simulated elements **311-314** can include virtual network routers or switches that are simulated by a traffic source emulation engine. Each of simulated elements **311-314** are respectively connected to simulated INT source elements/networks **302-306**. Likewise, router emulation **310** is logically coupled to simulation entities **321-324** in series. Notably, simulated topology **300** can be configured to provide a system administrator with a test INT simulation involving the generation of test system data packets that may contain one to five INT records. In the minimum possible scenario, the test system data packet may have only one INT record that represents router emulation **308** and in the maximum possible scenario, the test system data packet may have 5 records corresponding to elements **314**, **313**, **312**, **311**, and **308**. Although FIG. **2** depicts test port **301** connected to two simulation chains including five virtual network elements each, additional simulation chains comprising any number of virtual network elements can be utilized without departing from the scope of the disclose subject matter.

For example, if a system administrator required an INT test simulation involving a '3-record' INT test system data packet, traffic source emulation engine can be instructed to generate an INT test system data packet that includes telemetry metadata indicating that the test system data packet originated from a source (e.g., network **304**) and subsequently traversed simulated switch **312**, simulated switch **311**, and router emulation **308**. Traffic source emulation engine can then send the test system data packet to the device under test or system under test via port **301** of a network test tool device.

FIG. **4** illustrates a block diagram of test environment network **100** as comprising a network test tool device **102**, a system under test (SUT) **110**, and a switch DUT **116**, as similarly shown in FIG. **1**. As indicated above with respect to some embodiments, switch device **111** in SUT **110** may receive a test system data packet **120** from a network test tool device **102** over a data plane connection. Upon receiving the test system data packet **120**, switch device **111** may be configured to extract the contained emulated INT metadata from the received packet. Afterwards, switch device **111** can analyze the extracted telemetry data to determine whether a telemetry report needs to be generated and sent to an SDN controller device **112** in SUT **110**. Based on the telemetry metadata contents of the original test system data packet, the generation of a telemetry report message **124** can be triggered at switch device **111**. In some embodiments, the generation of a telemetry report message **124** can be triggered when certain flow parameters of the INT test system data packet **120** match predefined flow definitions. For example, switch device **111** functioning as an INT sink device can utilize a telemetry access control list, or flow watch list, that indicates which test system data packets are to be monitored by matching packet header fields. Telemetry reports are generated (by the INT sink device) for test system data packets that include parameters that match predefined definitions (e.g., source and destination address/port tuple data) specified in the flow watch list. Notably, telemetry report messages include information regarding the path that test system data packet **120** apparently/supposedly traversed in addition to other telemetry metadata, such as hop latency and queue occupancy and/or congestion.

In some embodiments, an INT sink device may initiate the generation of a telemetry report message **124** whenever a test system data packet matching a tracked application flow is received or transmitted on a different path than previously received packets. Further, the generation of a telemetry report message can be triggered at the INT sink device if a significant change in latency is indicated at a particular hop. The generation of telemetry report message **124** can also be triggered by various events indicated in the test system data packets, such as flow monitoring, queue congestion, and packet drops.

In some embodiments, telemetry report message **124** can be encapsulated by switch device **111** using IP and/or UDP. In some embodiments, such packet encapsulation facilitates the forwarding of the telemetry report message **124** from the INT sink device (e.g., switch device **111**) to the SDN controller device **112**. Notably, SDN controller device **112** can extract telemetry data from the received telemetry report message **124** and determine whether changes or modifications to emulated network **107** is necessary for continued testing of SUT **110**. After arriving at this determination, SDN controller device **112** can issue an instruction message **126** that is communicated via a different protocol (e.g., not P4-INT protocol). Notably, the instruction message **126** includes instructions for directing management engine **105** to initiate a subsequent INT test session or to modify the current INT test session.

For example, management engine **105** can logically modify emulated network **107** and/or change the type of metadata that the subsequent INT test system data packets should carry (e.g., configure test system data packets to include "queue occupancy" along with hop latency") after receiving instruction message **126** from SDN controller device **112**. Furthermore, management engine **105** may generate updated test system data packet configuration instructions for directing TSE engine **106** to generate test system data packets that contain telemetry metadata that indicates and/or represents the traversal of the test system data packet through a modified emulated network **107**. As indicated above, the telemetry metadata included in the INT test system data packets represents or specifies a packet traversal that did not actually occur (e.g., in a physical network). Rather, the telemetry metadata contained in the test system data packets are generated with complete telemetry information that represents a traversal through the emulated network from the onset.

FIG. **4** further depicts switch DUT **116** receiving a test system data packet **122** from network test tool device **102** over a data plane connection. Upon receiving the test system data packet **122**, switch DUT **116** may be configured to record its own INT metadata within received packet **122** and/or extract the INT metadata from the received packet. Based on the telemetry metadata contents extracted from the test system data packet, the generation of a telemetry report message **128** can be triggered at switch DUT **116**. In some embodiments, the generation of a telemetry report message **128** can be triggered when certain flow parameters of the INT test system data packets match predefined flow definitions. For example, switch DUT **116** functioning as an INT sink device can utilize a telemetry access control list, or flow watch list, that indicates which test system data packets are to be monitored by matching packet header fields. Telemetry reports are generated (by the INT sink device) for test system data packets that include parameters that match predefined definitions (e.g., tuple data) specified in the flow watch list. Notably, telemetry report messages include information regarding the path that test system data packets traversed (i.e., specifically, indicated that the test system data packets supposedly traversed) in addition to other telemetry metadata, such as hop latency and queue occupancy and/or congestion.

After generating telemetry report message **128** (with or without its own INT metadata), switch DUT **116** sends the telemetry report message to SDN controller emulation **118** in network test tool device **102**. Notably, SDN controller emulation **118** comprises an emulation element residing in emulated network **107** that is functioning as an SDN controller and is configured to receive and process the telemetry metadata report information contained in a telemetry report message **128** received from a switch DUT **116** via a receive port on the network test tool device **102**. For example, SDN controller emulation **118** can extract telemetry data from the received telemetry report message **128** and determine whether changes or modifications to emulated network **107** is necessary for continued testing of switch DUT **116**. After arriving at this determination, SDN controller emulation **118** can issue an instruction message (not shown, but similar to instruction message **126**) that is communicated to management engine **105** and that directs the engine **105** to initiate a subsequent INT test session or to modify the current INT test session. In some embodiments, management engine **105** can logically modify emulated network **107** after receiving instruction message from SDN controller emulation **118**. Furthermore, management engine **105** may generate updated test system data packet configuration instructions for directing TSE engine **106** to generate INT test system data packets that contain telemetry metadata that indicates and/or represents the traversal of the test system data packet through a modified emulated network **107**.

FIG. **5** is a flow chart illustrating an exemplary method **500** for testing network elements of an in-band telemetry capable network according to an embodiment of the subject matter described herein. In some embodiments, blocks **502-508** of method **500** may represent an algorithm performed by an INT management engine and/or an INT TSE engine that is stored in memory and executed by one or more processors of a network test tool device.

In block **502**, method **500** includes generating, by a network test tool device, at least one INT test system data packet that includes emulated INT instructions and emulated INT metadata that represents telemetry parameters corresponding to a plurality of emulated network devices. In some embodiments, the network test tool device includes a management engine that forwards test system packet generation instructions (e.g., test system data packet configuration instructions) to a traffic source emulation engine. The test system packet generation instructions include specifications that direct the TSE engine to create INT test system data packets that include telemetry metadata. Notably, the telemetry metadata included in the INT test system data packet represents the packet's supposed traversal or transit over several emulated network elements in an emulated network hosted by the network test tool device. The TSE engine is configured to emulate various network topologies in accordance with the instructions received from the management engine.

In block **504**, method **500** includes sending the at least one INT test system data packet to an INT network sink device. In some embodiments, the TSE engine is configured to transmit the test system data packet to the INT sink device via a data plane connection. Depending on the testing scenario, the INT sink device can either be network switching device that is either the device under test or a network element belonging to an SUT.

In block **506**, method **500** includes generating, by the INT network sink device, an INT telemetry report message derived from the emulated INT metadata extracted from the at least one INT test system data packet. In some embodiments, the INT network sink device may extract the telemetry metadata from the received INT test system data packet and generate a telemetry metadata report or digest.

In block **508**, method **500** includes forwarding the generated INT telemetry report message to a SDN controller entity. In some embodiments, INT network sink device is configured to send the generated telemetry metadata report to SDN controller entity. For example, the SDN controller entity can comprise a physical network element that belongs to a SUT. In an alternate testing environment scenario, the SDN controller entity comprises an SDN controller emulation that is hosted by the network test tool device.

It should be noted that each of the INT management engine, INT traffic source emulation engine, and/or functionality described herein may constitute a special purpose computing device. Further, the INT management engine, INT traffic source emulation engine, and/or functionality described herein can improve the technological field of computer network equipment testing. More specifically, the disclosed testing system can be configured to operate entirely within a test environment that supports an emulated network. As such, testing and monitoring the manner in which an INT sink DUT or an INT-capable system under test reacts to the receiving of emulated INT instructions and metadata contained in INT test system data packets generated by a network test tool device largely obviates the need to maintain a testing network comprising multiple network elements. Consequently, the network test tool device enables a system administrator to subject a DUT or SUT to INT-based testing without having to configure a physical network to generate the necessary INT metadata contained in an INT packet.

It will be understood that various details of the subject matter described herein may be changed without departing from the scope of the subject matter described herein. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

What is claimed is:

1. A method for testing network elements of an in-band telemetry (INT)-capable network, the method comprising:

generating, by a network test tool device, at least one INT test system data packet that includes emulated in-band telemetry (INT) metadata that indicates that the at least test system data packet has traversed emulated devices of an emulated network;

sending the at least one INT test system data packet to a system under test (SUT) that includes an INT sink device and a software defined network (SDN) controller for causing the INT sink device to generate and send an INT telemetry report based on the emulated INT metadata to the SDN controller and for causing the SDN controller to assess performance of the emulated network and issue an instruction message based on the assessment; and

receiving the instruction message from the SDN controller and evaluating, based on the instruction message, network assessment capability of the SDN controller.

2. The method of claim **1** wherein the instruction message comprises a non-INT instruction message containing one or more instructions that direct the network test tool device to modify a network topology of the emulated network and/or modify the INT instructions to record a different set of INT metadata within the at least one INT test system data packet than previous INT test system data packets.

3. The method of claim **2** wherein the network test tool device modifies the emulated INT metadata included in the at least one INT test system data packet to record a change in network topology.

4. The method of claim **1** wherein the telemetry parameters represent a user-defined test case specifying at least one predefined network event.

5. The method of claim **1** wherein the sending of the at least one INT test system data packet to the SUT causes to SDN controller to provide, to a management engine in the network test tool device, a status description indicative of real-time control functionality in response to receiving the INT telemetry report.

6. A system for testing network elements of an in-band telemetry (INT)-capable network, the system comprising:

a network test tool device comprising at least one processor and a memory;

an INT traffic source emulation engine that when stored in memory and executed by the at least one processor is configured for generating at least one INT test system data packet that includes emulated INT metadata that indicates that the at least test system data packet has traversed emulated devices of an emulated network, and for sending the at least one INT test system data packet to a system under test (SUT) that includes an INT sink device and a software defined network (SDN) controller for causing the INT sink device to generate and send an INT telemetry report based on the emulated INT metadata to the SDN controller and for causing the SDN controller to assess performance of the emulated network and issue an instruction message based on the assessment; and

a management engine for receiving the instruction message from the SDN controller and evaluating, based on the instruction message, network assessment capability of the SDN controller.

7. The system of claim **6** wherein the instruction message comprises a non-INT instruction message containing one or more instructions that direct the network test tool device to modify a network topology of the emulated network and/or modify the INT instructions to record a different set of INT metadata within the at least one INT test system data packet than previous INT test system data packets.

8. The system of claim **7** wherein the network test tool device modifies the emulated INT metadata included in the at least one INT test system data packet to record a change in network topology.

9. The system of claim **6** wherein the telemetry parameters represent a user-defined test case specifying at least one predefined network event.

10. The system of claim **6** wherein the sending of the at least one INT test system data packet to the SUT causes the SDN controller to provide to the network test tool device a status description indicative of real-time control functionality in response to the receiving the INT telemetry report.

11. A non-transitory computer readable medium having stored thereon executable instructions that when executed by a processor of a computer control the computer to perform steps comprising:

generating, by a network test tool device, at least one INT test system data packet that includes emulated in-band telemetry (INT) metadata that indicates that the at least test system data packet has traversed emulated devices of an emulated network;

sending the at least one INT test system data packet to a system under test (SUT) that includes an INT sink device and a software defined network (SDN) controller for causing the INT sink device to generate and send an INT telemetry report based on the emulated INT metadata to the SDN controller and for causing the SDN controller to assess performance of the emulated network and issue an instruction message based on the assessment; and

receiving the instruction message from the SDN controller and evaluating, based on the instruction message, network assessment capability of the SDN controller.

12. The non-transitory computer readable medium of claim **11** wherein the instruction message comprises a non-INT instruction message containing one or more instructions that direct the network test tool device to modify the INT instructions to record a different set of INT metadata within the INT test system data packet than previous INT test system data packets and/or modify network topology of the emulated network.

13. The non-transitory computer readable medium of claim **12** wherein the network test tool device modifies the emulated INT metadata included in the at least one INT test system data packet to record a change in network topology.

14. The non-transitory computer readable medium of claim **11** wherein the telemetry parameters represent a user-defined test case specifying at least one predefined network event or at least one predefined network condition.

15. The system of claim **11** wherein the sending of the at least one INT test system data packet to the SUT causes the SDN controller to provide to the network test tool device a status description indicative of real-time control functionality in response to the receiving the INT telemetry report.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 10,868,730 B2
APPLICATION NO. : 16/869129
DATED : December 15, 2020
INVENTOR(S) : Suvendu Mozumdar et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Title Page

Item (56), in Column 2, under "Other Publications", Line 1, delete "16/269,798" and insert -- 16/269,498 --, therefor.

Signed and Sealed this
Second Day of March, 2021

Drew Hirshfeld
Performing the Functions and Duties of the Under Secretary of Commerce for Intellectual Property and Director of the United States Patent and Trademark Office